# Analysis of Transient Clearances in a Gas Turbine Engine

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## ABSTRACT

Clearance prediction in rotating machinery is a complicated and interdisciplinary process that includes transient thermal-mechanical modeling of all components influencing clearance in one assembly model across a wide range of operational scenarios. This analysis process is typically referred to as a Whole Engine Model (WEM) within the aero and power generation gas turbine business. Understanding the transient evolution of the clearances enables manufacturers to optimize the performance and efficiency of an engine while reducing the risk of rubbing or other damage. The WEM can be utilized to understand not just the steady-state condition of a gas turbine engine when it is thermally soaked, but also the transient operations where thermal gradients and deltas and rotational loads have all a significant impact on the gap between the rotating and stationary parts.

Some of the primary advantages of using a WEM for clearance predictions are as follows:

a) reducing complexity and run time while maintaining accuracy
b) accounting for asymmetric effects (casing distortion, airfoil twist, mass accumulation)
c) updating the model based on new geometries and operating conditions
d) referencing boundary conditions from upstream simulation models (i.e. secondary air systems, boundary condition interdependency/links)
e) application of proprietary correlations for windage and heat transfer coefficients (HTC)
f) ability to split the model and therefore the workload into sub-models and later merge into one large assembly

Simcenter 3D, the tool used in this analysis, is a multiphysics platform which contains gas turbine specific tools and boundary conditions that enable analysts and engineers to capture relevant physics to ensure their clearance predictions are accurate across all operational scenarios. In addition, the CAD-centric approach to simulation allows users to quickly update their models when changes are required. This master model approach enables a true digital twin of the gas turbine engine.

The CAD-centric approach is used to show how modifying the thickness of stationary components can be used to obtain tighter tip clearances in the turbine. In addition, the modification of engine operating parameters during shutdown is also shown to significantly improve baseload/steady state clearances.

## INTRODUCTION

The WEM is a methodology taken within the power generation and aviation industry to model a complete gas turbine through a wide range of operational scenarios. Operational scenarios are defined as the sequence of starting, loading, baseload or cruising operation and de-loading to rundown until the engine is cooled. The thermal state of the engine, especially in power generation gas turbines, dictates when a restart can occur. Rubbing of stationary and non-stationary components can happen due to different thermal deformations of the respective components, which can cause mechanical damage to the engine as well as degradation of performance and efficiency.

## WEM MODELING PROCESS

To better understand the WEM, it is required to have a basic understanding of the gas turbine design process. There are many disciplines within the design process that must exchange data with each other. For example, the compressor and turbine aerodynamic design will impact the secondary air systems (SAS) and how cooling air for the hot turbine components will be routed and sized. The WEM plays the important role of combining the design elements from various design teams for the purpose of estimating transient component temperatures and clearance. Some of the typical disciplines in gas turbine design are shown in Figure 1.

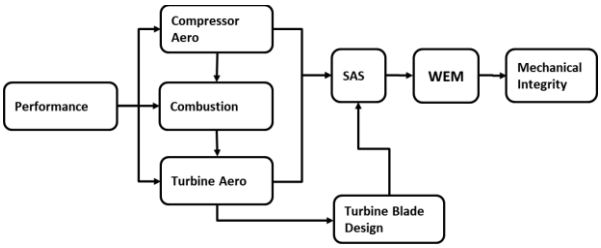



Fig. 1 Disciplines in gas turbine design process

The process for building the WEM involves starting from a CAD assembly, creating 2D and 3D bodies suitable for meshing, assigning materials, and applying boundary conditions. In addition to building the model, the inputs for the engine operating parameters must be prepared. This typically includes rotational speed, temperatures, pressures, and mass flows, as a function of time through the engine.

## MANAGING PARTS AND ASSEMBLIES

The boundary conditions and loads used in thermal and structural simulation are associated with geometry, and geometry modifications can easily be propagated through to the mesh and final simulation without having to make any major modifications to the model. For example, if a rotor designer decides to change the inner diameter of a disk, the analyst can reference this updated geometry in their model, and the mesh and simulation can be updated automatically.

WEM models typically contain many components and boundary conditions with varying inputs of heat rise and heat transfer correlations along the fluid network. To help manage such a complex model, different parts of the engine can be simulated independently and subsequently added together later in the design process to split workload and enable faster model building times. For example, one analyst could focus on the compressor, while another focuses on the turbine. Once those models are completed, they can both be added into an assembly, and all boundary conditions and constraints can be re-used at the assembly level. See Figure 2 below.

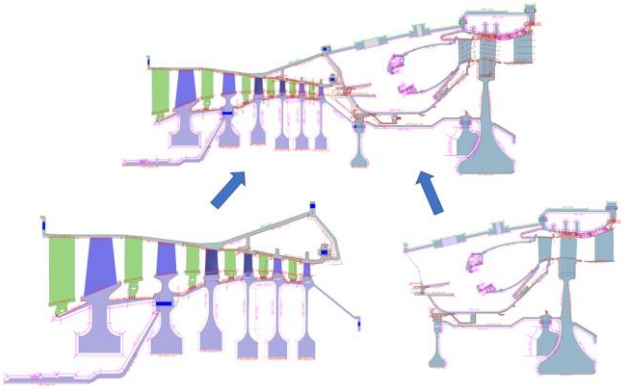


Fig. 2 WEM assembly of sub-models for working in parallel

# THERMOMECHANICAL MODELING

## MODELING FLUID NETWORK IN A WEM

Using spatial and time varying tables for convection is tedious to manage, is prone to user-errors, and does not model the fluid network with the correct physics. With interconnected turbine specific boundary conditions, users are only required to define inlet conditions, and the fluid temperatures and pressures are calculated in a conjugate manner based on the HTC and windage correlations specified in the analysis.

Time varying components within the boundary conditions are defined with key parameters in a condition sequence representing the mission or operational cycle. The condition sequence contains conditions representing engine states (take off, idle, max thrust, cruise, etc.) as defined by a set of parameters. Some typical parameters may be engine speed, mass flows, temperatures, and pressures, at various locations in the engine. Figure 3 shows some typical condition sequence parameters, as well as a graph of some of these parameters. T26, T30, T45, and T40, represent known transient operating temperatures along the engine. For example, T30 is typically compressor exit temperature.

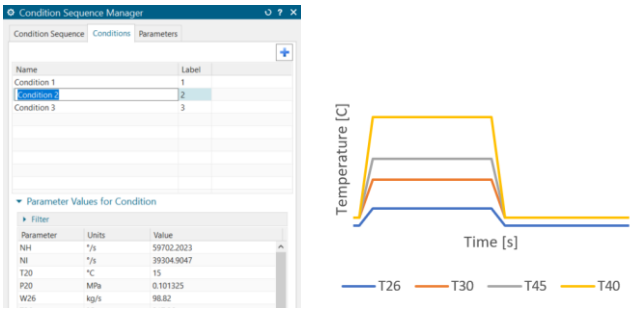



Fig. 3 Condition sequence parameters

In other words, the user can build a time-varying thermal-fluid network in their engine assembly and connect air streams together to ensure the correct physics are captured. Figure 4 shows the WEM assembly with a thermal-fluid network.

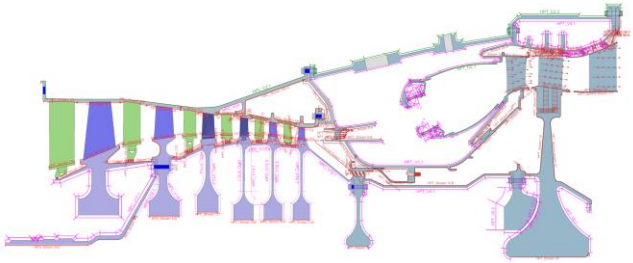


Fig. 4 WEM assembly with thermal-fluid network

Analysts can subsequently control and visualize the interdependencies in their whole engine model. Figure 5 illustrates this visualization of the first three compressor stages captured in an interactive html file allowing the engineer to inspect and ensure correct boundary condition interdependencies.

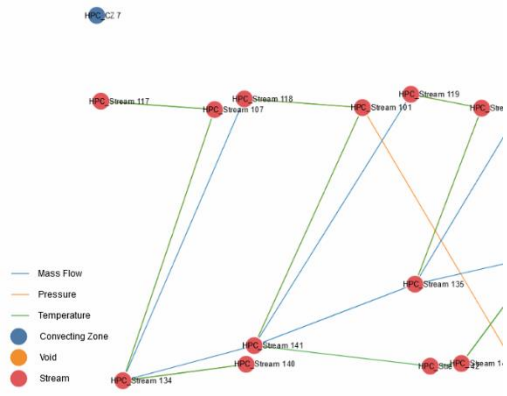



Fig. 5 Graphical representation of WEM interdependencies of the first three compressor stages

Users also have the ability to control which parameters are exchanged between the thermal and structural solver during an analysis. Pressures are typically sent from the thermal solver to the structural solver. The user also has the ability to pass displacements from the structural solver to the thermal solver and iteratively solve the coupled solution. This is useful in areas where HTC and windage may be sensitive to gap size, or where the user would like to couple mass flow to gap size.

## HOT RESTART CYCLE

In an ideal world, gas turbines would operate at known

environmental conditions and would have consistent component temperatures when the engine is started. This would enable a better prediction of design life of components. In reality, gas turbines operate depending on their application. Land based turbines for power generation are dependent on grid demand and infrastructure, and air borne engines are dependent on wind and other environmental factors.

Analysts typically run multiple condition sequences, or missions, which are chosen with the hope of determining worst case operating conditions. One such worst case scenario for clearance is a hot restart, which is when the engine shuts down for a short amount of time before restarting. When the engine shuts down, typically the casing cools down faster than the rotor which causes clearances to tighten. If the engine is then started from this condition, the pinch point (minimum transient clearance) is generally worse than it would be on a cold start. Considering this type of worst case scenario in the clearance analysis will ultimately lead to defining more open cold build clearance which reduces engine performance, but will mitigate the risk of having major rubbing events.

Two restart scenarios have been calculated for this engine, one for a 30 minute hot restart, and one for a 60 minute hot restart. Figure 6 shows the main engine operating parameters for the 60 minute hot restart cycle.

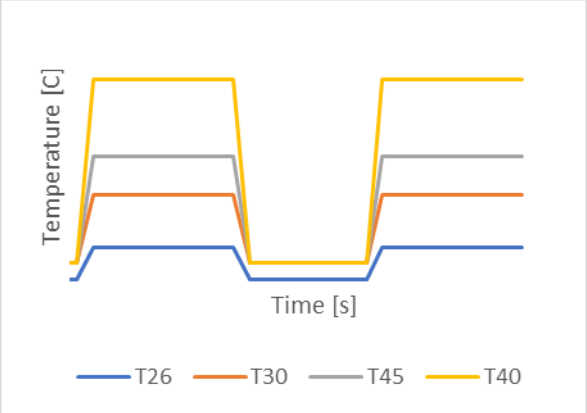



Fig. 6 Hot restart condition sequence parameters

## 2D ABSTRACTION AND ASYMMETRY

It is typical for WEM models to be represented in 2D, while in reality, clearances can vary around the circumference of the engine due to large asymmetries in the outer casing. Some examples of this include: the presence of a horizontal joint where the casing is bolted together (split plane), the combustor cans, the compressor air extraction holes, the turbine vane and respective cooling network, the leaning and twisting of airfoils, or the movement of the bearings (where the rotor is supported).

The multiphysics tool and its CAD Engine allows engineers to make appropriate cuts and projections from the 3D CAD to the 2D for WEM simulation. The parts of a gas turbine that are asymmetrical are modeled with a thickness property that accounts for the mass of the parts enabling accurate modeling of the thermal inertia of the components.

This particular multiphysics tool allows users to include 3D geometries into the WEM to enable more accurate calculations of asymmetric distortions. Figure 7 illustrates this approach where we see a 3D casing integrated into the typically 2D WEM.

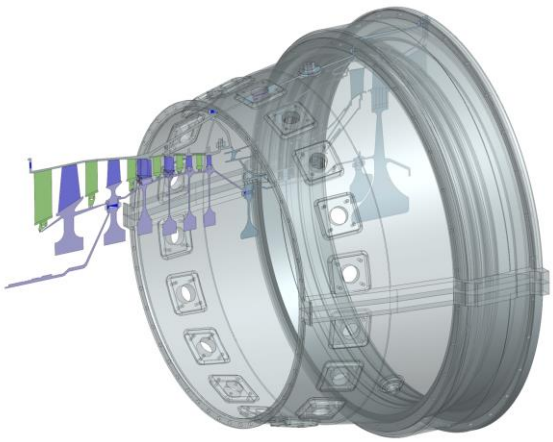


Fig. 7 WEM with 3D Casing

Another mixed 2D/3D scenario includes a 3D blade in combination with a 2D rotor (below the blade root). This allows a more direct way of calculating thermal contact conduction and convection in the blade root and avoids the use of complicated area factors that are required in 2D approximations. Periodic features can be accounted for by specifying the number of instances and allowing the solver to account for appropriate thermal mass, capacitance, and convective area. This enables gas turbine engineers to examine in closer detail areas that require higher fidelity modeling, such as turbine blade roots to model 3D conduction/convection and blade aerodynamic forces. An example of a mixed 2D/3D model with two 3D compressor blades integrated into the WEM is displayed in Figure 8.

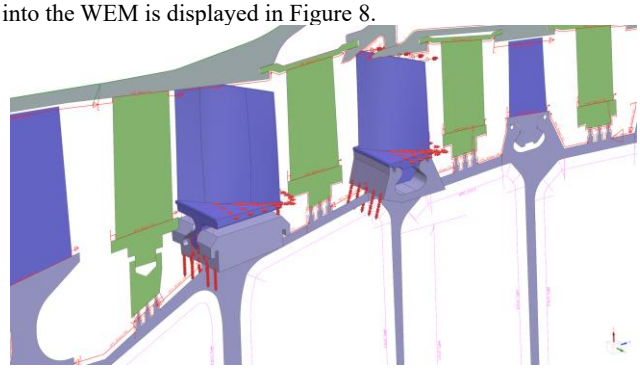


Fig. 8 WEM with 3D Blade

In addition to including 3D solid bodies, users have the ability to include 3D fluid bodies or domains to model CFD in critical cavities to accurately predict convection in a thermal-flow coupled model. These 3D fluid bodies can also be connected with the existing WEM thermal-fluid network. Figure 9 shows the fluid domain incorporated into a WEM and the corresponding fluid velocity results.

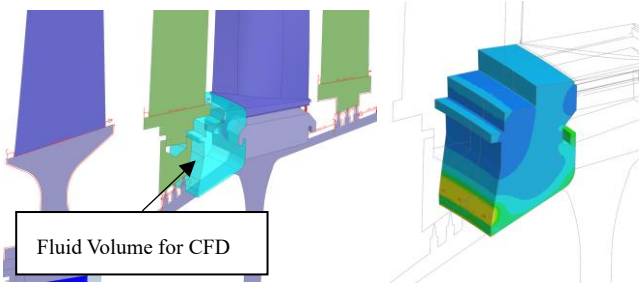



Fig. 9 WEM with 3D fluid volume for CFD (Left) and WEM CFD velocity contours (right)

## WEM WITH 3D CASING MODEL SETUP

To attach a 3D geometry to a 2D geometry, modeling objects must be applied in the structural and thermal domains for the thermomechanical model. The image below shows such a region, where a mixed 2D axisymmetric and plane stress region is connected with a 3D geometry at a casing flange. One node on the 2D region is structurally coupled with corresponding nodes around the circumference of the 3D mesh and is coupled in all directions of the cylindrical coordinate system. Thermal contact can easily be simulated via selections of the 2D edge and 3D face and by specifying an appropriate HTC. Figure 10 shows an image of where these coupling regions are located.

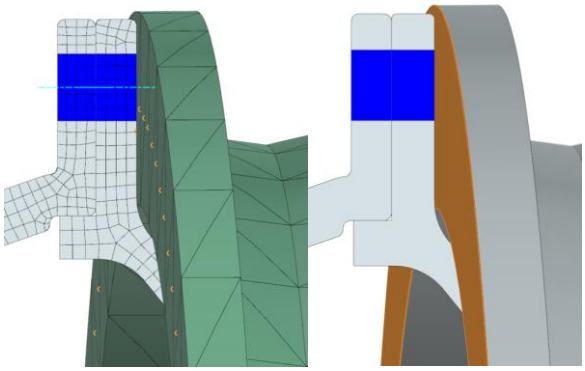


Fig. 10 WEM with 3D casing showing coupling regions for 2D to 3D connections

For convective thermal boundary conditions in general, they can be applied on edges of 2D bodies or faces of 3D bodies. Figure 11 shows the comparison of the ring segment flowpath convection load on a 3D ring segment and its 2D equivalent.

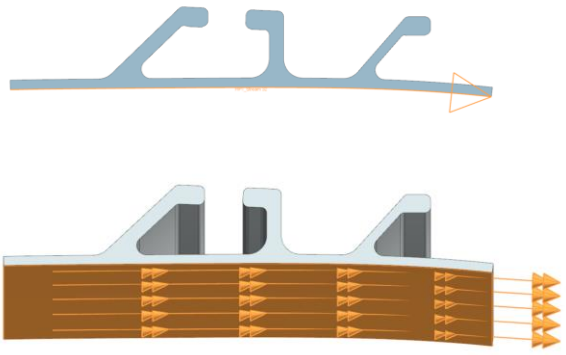


Fig. 11 Equivalent convective loads on 2D and 3D geometry

The vane cooling supply air channel is supplied from the compressor at 2 circumferential locations. As the air passes circumferentially through this cavity from the injection point to the various vanes, it is possible this air will pick up some heat from the surrounding hot metal. This heat pickup can be simulated using a 1D duct element and some duct-surface convective couplings. The mass flow applied to the 1D duct reduces as the cooling air gets further away from the injection point. Using 1D ducts allows the user to model the fluid flow in a lightweight manner that doesn't add significant solve time. Figure 12 shows a portion of the duct used for fluid modeling as well as the injection points. The 1D duct injection point is tied to the other thermal boundary conditions in the model and are included in a solve with the rest of the WEM.

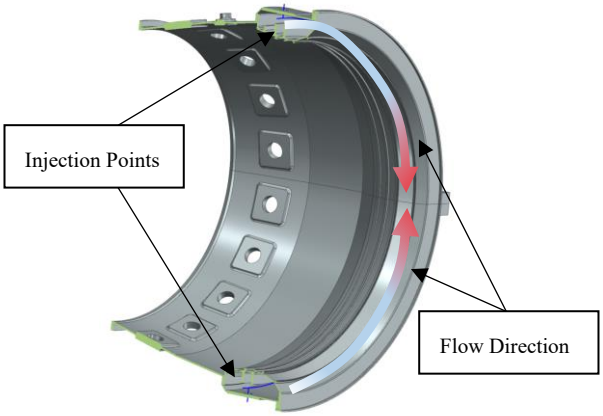



Fig. 12 Clip view showing vane supply injection points and flow direction. The blue line is the 1D duct.

## CUSTOM CORRELATIONS

Users can access fluid properties and results during the solve in a custom plugin to calculate HTC or heat pickup in various regions of their models based on correlations. Virtually any type of quantity can be calculated in a custom plugin. In this way legacy know-how and in-house knowledge can be captured, stored and leveraged to ensure the highest fidelity of the model.

One such correlation is the windage rise in a conical cavity which is shown below [1] in Figure 13. This correlation can improve the physics of the fluid-surface interface for a conical feature and aid in the calculation of windage rise along a stream of fluid.

$$\Gamma_{R_{cone}} = \frac{0.044 \text{ sign}\,(\beta - S_f)|\beta - S_f|^{-0.65}|\beta|^{0.65}\rho(\beta - S_f)^2\Omega_{ref}^2(r_3^5 - r_2^5)Re^{-0.2}}{\sin\alpha}$$

Where,

| | |
|---|---|
| $\Omega$ | Angular velocity |
| $\Omega_{ref}$ | Angular velocity of reference rotor |
| $\beta$ | Ratio of $\Omega/\Omega_{ref}$ |
| $S_f$ | Swirl factor |
| $r_n$ | radius at point n |
| $\alpha$ | Angle of the conical surface from horizontal |
| Re | Disk Reynolds number |
| $\Gamma_{R.cone}$ | Rotor torque for cone |
| $\rho$ | Density of fluid |

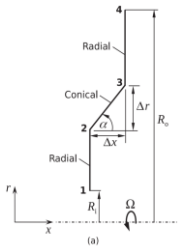



Fig. 13 Correlation for rotor torque of a conical feature implemented in thermal plugins [1]

## THERMAL MAPPING

For WEM analysts who need to exchange data with structural analysts, there is a range of possibilities available. In this instance the built-in capabilities of Simcenter 3D were employed. The mapping solution enables users to map temperatures from mixed 2D/3D simulation models to mixed 2D/3D target models with meshes from various analysis tools. This allows flexibility to integrate the WEM process into an organizations' existing analysis workflow. Figure 14 shows the source model alignment tool, where the source model in blue overlays the target structural model.

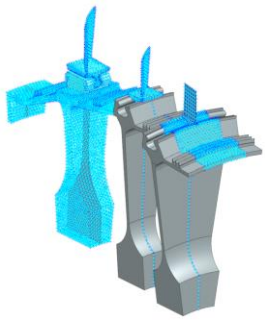


Fig. 14 Thermal mapping from thermal solution to structural solution

## THERMAL-STRUCTURAL RESULTS

### CLEARANCE ANALYSIS

Figure 15 below shows the evolution of turbine tip gap closure generated within the Simcenter post environment, where nominal steady state condition occurs at 5000[s]. You can see here the minimum value occurs around 5500[s] which is during engine shutdown. This minimum value, or pinch point, is important because it corresponds to cold build clearance and impacts how tight the clearances can be at steady state. The steady state clearance (or baseload / cruising clearance) is most simply calculated as the difference between the pinch point closure and that at steady state, which in this case is about 1.1[mm]. In an ideal engine, the minimum clearance would occur at steady state so near-zero clearance can be achieved.

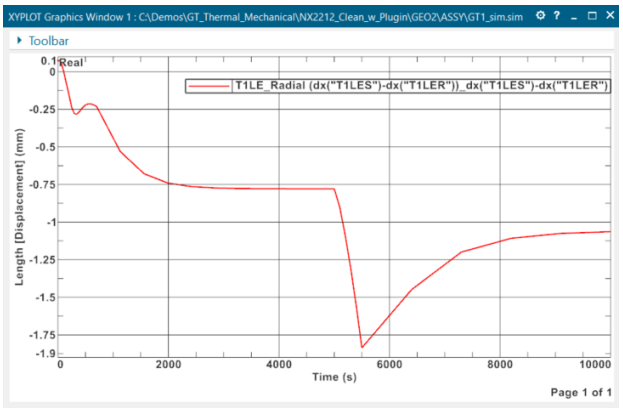



Fig. 15 post processing of tip gap closure from result probe

With this particular tip gap being a radial tip gap, there is no need to look at the axial contribution due to thermal growth of the casing and rotor from the engine fixation point (i.e.. Bearing). With radial growth of components being the primary driver for clearance, the transient temperature profile of the major load bearing components should be inspected. Figure 16 shows temperature profile of the rotor and stator at the pinch point time, as well as the transient average temperature of the turbine vane carrier (TVC) (blue curve) and rotor disk (green curve) in the chart on the right. It's observed here the TVC temperature drops much faster than the rotor, which is a very typical scenario in gas turbine thermal growth behavior.

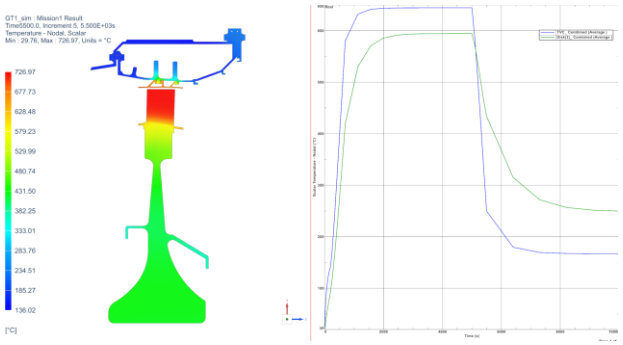


Fig. 16 post processing of temperatures of rotor disk and TVC

To enhance thermal matching of the rotor and casing there are many options to consider, including: adding some thermal mass to the TVC or to decrease the cooling air mass flow passing through the TVC on shutdown. Using expressions and associative coupling between CAD and simulation within Simcenter makes these geometric modifications and studies quite easy. Figure 17 shows a screenshot of the modified casing geometry and temperatures. Figure 17 also shows a graph of tip gap closure comparing the baseline clearance against the case with a thicker TVC, as well as the case with reduced mass flows on shutdown.

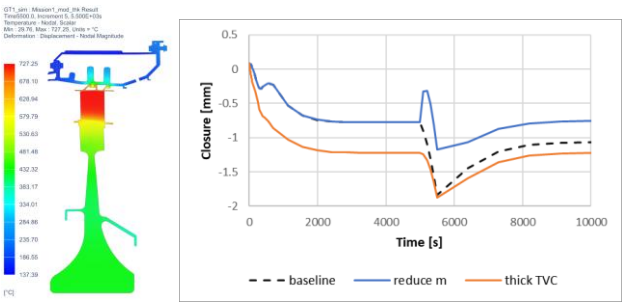



Fig. 17 tip gap closure with reduced mass flow and thicker TVC compared to baseline design

From this design sensitivity, it's observed the most promising mechanism for improving clearance control is to reduce mass flows on shutdown passing through the TVC, and results in a steady state clearance of about 0.4[mm]. Making the TVC thicker also improves the behavior, resulting in a steady state clearance of about 0.7[mm]. The decision on how to improve clearance must be balanced with the cost of added material and design complexity, as well as the efficiency gain resulting from this clearance improvement. Additional off-design conditions/cycles must also be checked.

### 3D EFFECTS AND OVALIZATION

The typical approach of calculating transient clearances based on 2D geometries and meshes leaves clearance analysts in a difficult position when trying to define clearances for cold build assemblies to prevent large rubbing events in a real engine. As observed for this particular engine, we will see the inclusion of a bolting flange on the outer casing causes the casing to ovalize. Figure 18 shows the displacement and thermal contour results of the engine showing the 2D and 3D results. Notice the lower displacements and temperatures near the horizontal bolting flange.

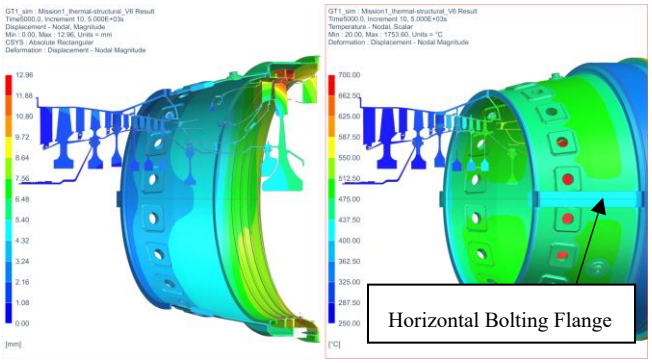



Fig. 18 2D and 3D displacement and thermal results at steady state

To get a better idea of transient clearance the radial displacement at different circumferential positions for the stationary component at stage 1 turbine blade tip is shown in Figure 19. It is assumed the rotor centerline and casing centerline are the same.

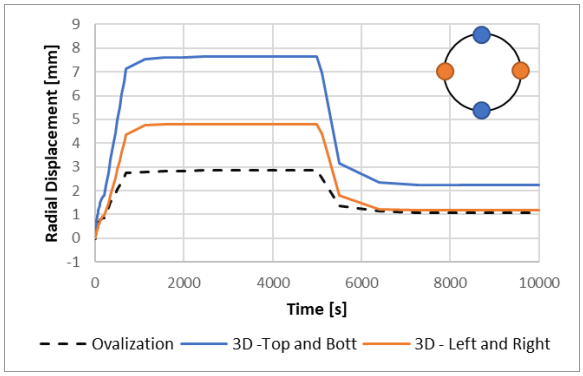



Fig. 19 Radial displacement of outer casing

The transient ovalization curve is added to the 2D clearance curve to obtain the 3D top, bottom, left, and right clearances. See Figure 20 below.

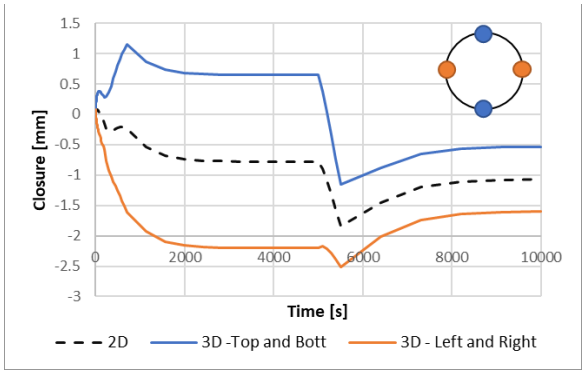



Fig. 20 3D vs 2D Tip Clearance

With such high ovalization quantities relative to 2D clearance, further clearance studies should be made to try to keep a more uniform circumferential clearance. Some potential mitigations may include adding some stiffening ribs to the casing, or using active thermal control measures on the casing.

## 3D FLUID TEMPERATURES

It may be useful to turbine component designers as well as secondary air systems analysts to post process fluid temperatures around the circumference of the engine which supply the vanes. Figures 21 and 22 show the changing vane cooling supply temperature around the circumference. Notice there is about a 6[C] delta at steady state (5000[s]), and a peak delta temperature around 40[C] during the shutdown as mass flows are reduced.

The 6[C] delta in vane cooling supply temperature will surely impact material temperatures of the vanes near the horizontal bolting flange and should therefore be considered by turbine component designers in design life calculations.

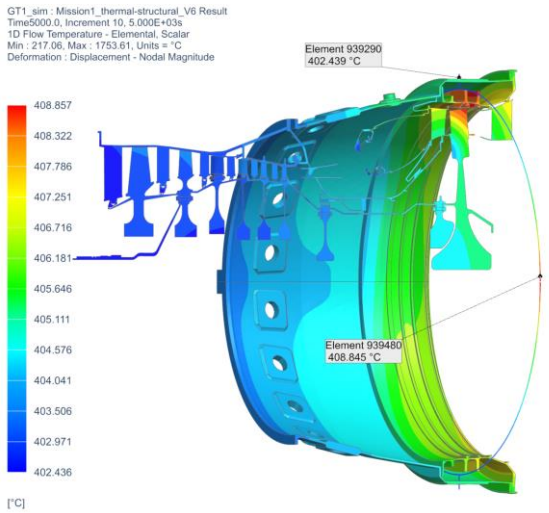



Fig. 21 Fluid temperature contour around circumference at steady state

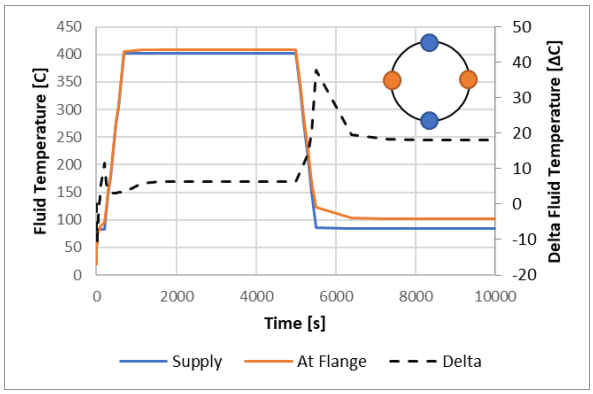



Fig. 22 Transient fluid temperature results

## HOT RESTART

The clearance results of leading and trailing edge are shown in Figure 23. It was observed during operation the leading edge opens and the trailing edge closes, which is due to the blade tilting in the upstream direction. This is shown in a deformed plot in Figure 24. The hot restart did not show a worst case scenario for clearance in this case and the worst case scenario for stage 1 turbine blade tip is a cold start.

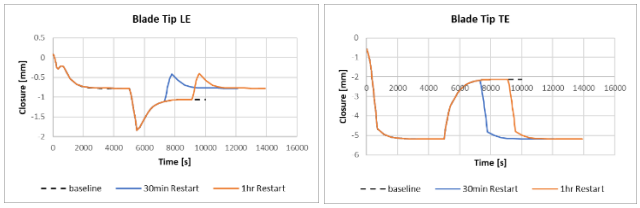



Fig. 23 Transient hot restart clearances of leading and trailing edge

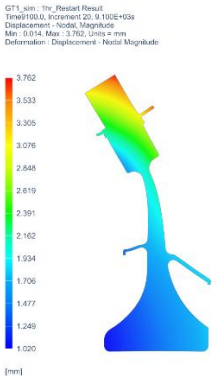



Fig. 24 Deformed displacement contour of turbine disk and blade showing tilting

## CONCLUSION

The WEM process enables engineers and analysts to understand the transient thermal mechanical behavior of a gas turbine engine. Simcenter 3D Multiphysics offers users a comprehensive and complete toolset to incorporate complicated physics into a WEM to enhance the accuracy of clearance predictions. Users can include 3D effects directly into their WEM to account for asymmetric effects. All of this translates to higher operational efficiencies and power outputs, while maintaining and often enhancing the reliability of the gas turbine engines.

The CAD-centric platform enables analysts to quickly update simulations based on geometry changes and run various operating conditions necessary in evaluating clearances for all conditions. In this case it was observed adjusting the shutdown mass flows and adding mass to the TVC impacted the clearances significantly, from about 1.1[mm] down to 0.4[mm] for the reduced mass flow case.

The inclusion of a 3D casing revealed significant ovalization for this engine, resulting clearance deltas of about 3[mm] when comparing horizontal and vertical clearances. Further clearance optimization studies should be undertaken to mitigate this ovalization.

The approach to model varying circumferential vane supply temperature with 1D ducts showed a 6[C] temperature rise in the supply cavity going from the injection point to the horizontal bolting flange. This 6[C] temperature rise could be critical depending on design margins and needs to be included in secondary air system and design life calculations.

For this specific engine, simulating hot restart scenarios did not show a worst case scenario for turbine blade tip clearance. Regardless, hot restarts should be checked for varying operating conditions and for other clearances in the engine.

## REFERENCES

[1] Bijay, K., Sultanian, 2018, “Gas Turbines Internal Flow Systems Modeling”, Cambridge University Press.